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Research Paper

Design Fatigue Lives of Polypropylene Fibre Reinforced Polymer Concrete Composites

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Flexural fatigue behavior of Poly-propylene fibre reinforced polymer concrete composites (PFRPCC) has been investigated at various stress levels and the statistical analysis of the data thus obtained has been carried out. Polymer Concrete Composite (PCC) samples without addition of any type of fibres were also tested for flexural fatigue. Forty specimens of PCC and One hundred and Forty One specimens of PFRPCC containing 0.5%, 1.0% and 2.0% polypropylene fibres were tested in fatigue using a MTS servo controlled test system. Fatigue life distributions of PCC as well as PFRPCC are observed to approximately follow a two parameter Weibull distribution with correlation coefficient exceeding 0.9. The parameters of the Weibull distribution have been obtained by various methods. Failure probability, which is an important parameter in the fatigue design of materials, has been used to obtain the design fatigue lives for the material. Comparison of design fatigue life of PCC and PFRPCC has been carried out and it is observed that addition of fibres enhances the design fatigue life of PCC.

1 Introduction

Polymer concrete composites (PCC) had been developed as alternative materials for construction industry in early 1960’s wherein its early usage has been reported for building cladding etc. Later on because of rapid curing, excellent bond to cement concrete and steel reinforcement, high strength and durability, these were extensively used as repair material. Further, Precast Polymer concrete has been used to produce a variety of products like acid tanks, manholes, drains, highway median barriers etc[1].Use of PCC in machine tool applications has been reported since late 70’s wherein these have been used to replace materials including metals like cast iron for machine tool bases[2–5]. Lot of research has been

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reported on the mechanical properties of polymer concrete composite in the last few decades. Properties like compressive strength, flexural strength, split tensile strength, damping have been evaluated to a great extent for these materials [6–10].

Addition of glass fibres, steel fibres, carbon fibres etc. is reported to enhance the mechanical properties of polymer concrete composites and the resulting material is known as fibre reinforced polymer concrete composite (FRPCC) [11–13]. The use of PCC in machine construction calls for evaluation of the fatigue performance of the material, which till date has been studied to a very limited extent [14–16]. Large variability usually exists in the fatigue strength/life results obtained through experimental investigations at a given stress level, even under carefully controlled test procedures. The same was taken care of by providing higher safety factors earlier. However, optimum design these days requires accurate characterization of this variability for the materials. The dispersion of fatigue life has, therefore, been a subject of statistical analysis by various researchers[17–20].As per the knowledge of the authors, no study has been reported on the fatigue behavior of FRPCC. The present investigation was therefore planned to evaluate the fatigue behavior of fibre reinforced polymer concrete composites, FRPCC. The results reported in this paper are a part of a comprehensive investigation underway at the author’s institute to study the effect of fibre addition in PCC on their fatigue performance.

2 Experimental Procedure

Epoxy resin, LAPOX- B47 along with hardener LAPOX- K46 supplied by M/s Atul Ltd., Mumbai has been used in this investigation. The hardener and resin have been mixed in the ratio of 1:2 by weight. Resin dosage of 10-14% by weight of PCC has been reported in literature when using coarse aggregates [21,22] whereas higher resin dosages up to 20% have reported when using only sand as aggregate material[8]. Resin dosage of 12% by weight of PCC has been used in this investigation. Aggregate grading plays an important role in the final properties of PCC and therefore an optimized aggregate mix suggested in literature has been used in this study[23]. Locally available crushed gravel has been used as aggregate in PCC. The aggregate mix had been optimized based upon the least void content criteria. A micro filler is also often added to PCC mix to reduce the void content in aggregate mixture and thereby increase the strength of PCC. Fly ash is a byproduct of the coal burning in power plants and is used as a filler because of its easy availability and because its usage in PCC is reported to yield better mechanical properties as well as reduced water absorption[24]. Addition of fly ash also improves the workability of fresh PCC mix resulting in products with excellent surface finish[25]. F-type fly ash has been used in the ratio of 10% by total weight of PCC in this study.

Macro-Monofilament type synthetic poly-propylene fibres of average length 12 mm were added into PCC. The fibre dosage was kept at 0.5%, 1.0% and 2.0% by weight of PCC. The workability of the PCC and PFRPCC mix is an important parameter, as a good workability will ensure proper filling of the molds and will also result in less internal voids in the material. Increasing the amount of resin used in manufacture of PCC/PFRPCC improves the workability and its flow. The polymer binder, however, is the most expensive constituent and hence increasing its proportion makes PCC/PFRPCC more expensive. Generally, it is recommended to use enough resin, to produce the minimum degree of workability which is acceptable. There are no specified workability tests for PCC and PFRPCC mixes. Vee-Bee consistometer test as per *IS-1199:1959*, which determines the time required for transforming by vibration fresh concrete in the shape of a conical frustum into a cylinder, was used to evaluate the consistency and workability of PCC and PFRPCC mixes. It is observed that the time taken by the mix to fully settle down increases with increase in the fibre content in the mix. Although, no guidelines for Vee-Bee Time test for PCC/PFRPCC are available in literature, sufficient workability was observed for all the mixes evaluated in this investigation for the aggregate mix, resin content, fly ash content and fibre contents stated in Table-1.

Details of the materials used in this study are provided in Table-1.The specimens of 40x40x160 mm size were cast on a vibratory table using the materials listed above. The specimen size has been chosen as per RILEM PC-2 –TC113 and has been used by a number of researchers in their work on polymer concrete[8,9]. Aggregate material and fly ash was dried before preparation of samples to reduce moisture content below 0.5 % as it has been reported that moisture content of aggregates has a deleterious effect on the properties of polymer concrete[26]. The specimens were cured at room temperature for 7 days before conducting the fatigue tests as per method adopted by a number of other researchers[27–29].

Table 1- Materials used for PCC and PFRPCC

Aggregate (Crushed Gravel)	
Particle Size (mm)	Quantity (% of total aggregate weight)
4.76- 9.52	39.6%
2.38-4.36	33.5%
0.15- 0.3	26.9%
Resin & Hardener system	
Description	Quantity (% of total weight of PCC)
(LAPOX- B47 & K-46)	12 %
Micro filler	
Description	Quantity (% of total weight of PCC)
F –Type Fly Ash	10%
Fibre Reinforcement	
Description	Quantity (% of total weight of PCC)
Macro Monofilament poly-propylene fibres	0.5%, 1.0%, 2.0%

The estimation of static flexural strength (f_r) of the test material is a pre-requisite for the selection of maximum and minimum loads to be applied in particular fatigue test. The static flexural strength of the PFRPCC specimens was, therefore, evaluated prior to fatigue testing using MTS servo controlled test system at a loading rate of 0.5 mm/min, which is used by some of the previous investigators [18-19]. Generally, 4-5 specimens from a particular batch were randomly selected and tested to determine their static flexural strength. An average static flexural strength of 27 MPa was obtained for PFRPCC containing 0.5% fibres. It is observed that the addition of poly-propylene fibres enhances the static flexural strength of PCC to a limited extent. An increase of 9% in static flexural strength is observed by addition of 0.5% fibres by weight when compared to PCC. Further addition of fibres up to 1.0% does not enhance the static flexural strength significantly and an average static flexural strength of 27.5 MPa was achieved for PFRPCC containing 1.0% fibres. The static flexural strength of PFRPCC containing 2.0% fibres is reduced to 24.7 MPa.

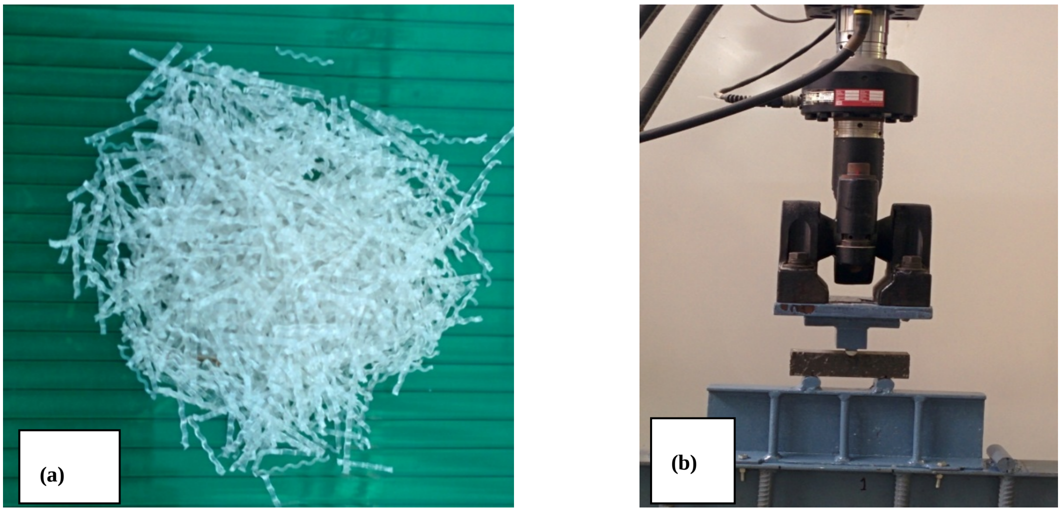

Fig. 1 (a) Macro Monofilament Poly-propylene fibres (b) Loading arrangement

All the fatigue tests were carried out on a 100 kN MTS- Cyclic load testing facility in three point bending mode. The loading span was taken as 100 mm. The ratio of minimum fatigue stress to maximum fatigue stress in one cycle of loading in a fatigue test is defined as the stress ratio Rand was maintained at 0.1 in all the fatigue tests. The fatigue tests were carried out at a frequency of 10 Hz and constant amplitude, sinusoidal, non-reversed loads were applied. The minimum fatigue stress (f_{min}) and maximum fatigue stress (f_{max}) to be applied on test specimen was selected from f_r and a particular stress level 'S' (f_{max}/f_r). For each mix, the first test was conducted at the highest possible stress level and the number of cycles to failure was noted as fatigue life 'N'. Subsequent tests were conducted by lowering the stress levels in a systematic manner. Since fatigue testing is a time consuming and expensive process and a large number of specimens were proposed to be tested, an upper limit of number of cycles to be applied was fixed depending upon the availability of testing equipment and time constraints. A particular test was terminated as and when the failure of the specimen occurred or the upper limit was reached, which ever was earlier. Fig. 1 presents the details of the loading arrangement and a view of the macro polypropylene fibres used in this investigation.

3 Analysis of Fatigue Life Data

The complete fatigue life data obtained at various stress levels for PCC is provided elsewhere by the authors [30] and for PFRPCC having 0.5%, 1.0% and 2.0% weight fraction of fibres is listed in ascending order in Table 2, 3 and 4 respectively. Some data points in fatigue life data deserve consideration for rejection as outliers. Chauvenet's criterion [31]was applied to the data points at all the stress levels tested in this investigation, and data points meeting this criterion for rejection were identified and excluded from further analysis.

Table 2- Fatigue life data for PFRPCC-0.5%

S= 0.85	S= 0.8	S= 0.75	S= 0.7
5088	1806*	60023	153452
7021	17612	87903	182345
9954	20438	136458	245784
11931	39974	165874	392145
12351	40124	170267	524876
13214	46299	172367	752318
16134	47129	196325	812019
19232	55101	237737	862546
19703	65235	325445	985357
19841	70124	434540	1102489
--	80163	--	2000000**

** Rejected as Outlier by Chauvenet's criteria, not included in analysis*
*** Run out, not considered in analysis*

Table 3 - Fatigue life data for PFRPCC-1.0%

S= 0.85	S= 0.8	S= 0.75	S= 0.7
7789	95*	123565	201326
7852	35382	149862	295623
8526	45325	154781	345625
9347	55367	200356	402351
12451	55559	207461	463589
14633	67096	260177	736324
16836	73529	367834	869247
17905	77851	498657	1133565
21199	118677	656834	1326546
28193	158954	698652	1632581
--	175301	--	2000000**

** Rejected as Outlier by Chauvenet's criteria, not included in analysis*
*** Run out, not considered in analysis*

Table 4 – Fatigue life data for PFRPCC- 2.0%

S= 0.85	S= 0.8	S= 0.75	S= 0.7
7033	35628	95258	142038
8547	47723	120325	175623
9865	57072	145265	250382
9956	78658	200382	421539
11617	84807	240526	520152
13237	85629	326080	628405
14252	126562	338038	756214
23220	175684	649115	956203
25624	185647	785624	1425870
27987	232437	800265	1754735
--	80163	--	2000000**

** Rejected as Outlier by Chauvenet's criteria, not included in analysis*
*** Run out, not considered in analysis*

The probabilistic analysis of fatigue life data was carried out using a two-parameter Weibull distribution function which is characterized by a cumulative distribution function (CDF), $F(n)$ as follows:

$$P_f(n) = 1 - \exp\left[-\left(\frac{n - n_{o,s}}{u - n_{o,s}}\right)^{\alpha}\right] \tag{1}$$

where n = specific value of the random variable N; u = scale parameter or characteristic life at stress level S; α = shape parameter or Weibull slope at stress level S and $n_{o,s}$= location parameter or minimum life at stress level S.

In fatigue applications, the minimum life $n_{o,s}$ can reasonably be assumed equal to zero. Equation (1) thus reduces to the following form:

$$F(n) = 1 - \exp\left[-\left(\frac{n}{u}\right)^{\alpha}\right] \tag{2}$$

3.1 Analysis of fatigue life data by graphical method

The probability of survival or survivorship function or reliability function, $L_R(n)$, may be defined as $L_R(n) = 1 - F(n)$, and substituting this value of $F(n)$ in equation (2) and further taking logarithms, it is modified to:

$$\ln\left[\ln\left(\frac{1}{L_R}\right)\right] = \alpha\ln(n) - \alpha\ln(u) \tag{3}$$

Equation (3) represents a linear relationship between $\ln[\ln(1/L_R)]$ and ln(n). In order to obtain a graph from (3), the fatigue-life data corresponding to a particular stress level are first arranged in ascending order of cycles to failure and the empirical survivorship function L_R for each fatigue-life data at a given stress level is obtained from the following relation[31]:

$$L_R = 1 - \frac{i}{k+1} \tag{4}$$

where i denotes the failure order number and k represents the number of data points in a data sample under consideration at a particular stress level S.

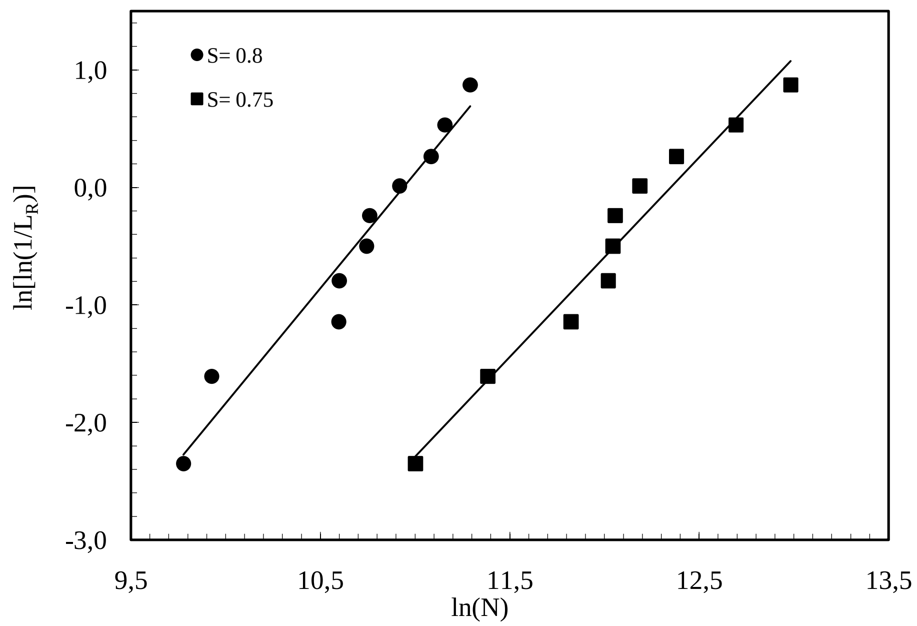

Fig. 2 Graphical analysis of fatigue life data for PFRPCC-0.5%

The empirical survivorship function in the form of ln [ln(1/L_R)] for each fatigue-life data is then plotted on a graph with the corresponding fatigue lives ln(N). If a linear trend is established for the data points, the best fit line is drawn using method of least squares. It can then be assumed that fatigue-life data for that particular stress level follows the two-parameter Weibull distribution. Fig. 2 presents the fatigue life data for few selected stress levels plotted as described above for PFRPCC-0.5%. The approximate straight line plots in this figure with statistical correlation coefficients “r” exceeding 0.9, indicate that the two-parameter Weibull distribution is a reasonable assumption for the statistical distribution of fatigue-life for PFRPCC-0.5%. Similar results have been obtained for PFRPCC-1.0% and PFRPCC-2.0%, at all the stress levels in this investigation. The estimated parameters thus obtained are listed in Table 5.

Table 5 - Parameters of Weibull distribution for PFRPCC

PFRPCC-0.5%						
Stress	Graphical Method		Method of Moments		Average Values	
Level, S	α	u	α	u	α	u
0.85	2.152	15560	2.764	15108	2.458	15334
0.80	1.956	56315	2.554	54307	2.255	55311
0.75	1.698	230791	1.872	223880	1.785	227335
0.70	1.342	709720	1.808	676415	1.575	693067
PFRPCC-1.0%						
Stress	Graphical Method		Method of Moments		Average Values	
Level, S	α	u	α	u	α	u
0.85	2.110	16685	2.294	16335	2.202	16510
0.80	1.808	99653	1.870	97233	1.839	98443
0.75	1.500	384798	1.599	370043	1.550	377421
0.70	1.396	855413	1.568	824716	1.482	840065
PFRPCC-2.0%						
Stress	Graphical Method		Method of Moments		Average Values	
Level, S	α	u	α	u	α	u
0.85	1.966	17485	2.101	17087	2.033	17286
0.80	1.578	128478	1.740	124604	1.659	126541
0.75	1.254	424143	1.387	405576	1.320	414859
0.70	1.165	801989	1.333	766089	1.249	784039

3.2 Parameter estimation by method of moments

Estimating parameters by method of moments requires estimating the appropriate sample moments, such as sample mean and sample variance. A simple expression for finding the value of shape parameter α is provided in literature as follows[32]:

$$\alpha = (CV)^{-1.08} \tag{5}$$

The characteristic life u can be estimated from (5) by substituting μ for $E(n)$ as follows:

$$u = \frac{\mu}{T\left(\frac{1}{\alpha}+1\right)} \tag{6}$$

The parameters obtained by this method for PFRPCC at different stress levels are also listed in Table 5.

3.3 Estimation of design fatigue life

The fatigue life data obtained in this investigation for PFRPCC witness large scatter. This is usually expected in the fatigue life data even at a given stress level under carefully controlled test procedures. For PCC reinforced with fibres i.e. PFRPCC, this variability in the distribution of fatigue life substantially increases compared to that of plain PCC. The design fatigue life N_D, should be selected such that there is only a small probability that a fatigue failure will occur. Once the distribution function is determined as above, the design fatigue life N_D may be selected corresponding to an acceptable probability of failure. The design reliability may be expressed as $L_N [N > N_D] = 1 - P_f$, in which P_f is the probability of failure. Thus the design fatigue life N_D corresponding to a permissible probability of failure P_f can be obtained from (3) as follows [19]:

$$N_D = u\left[\ln \frac{1}{1-P_f}\right]^{\frac{1}{\alpha}} \tag{7}$$

Using the average values of the Weibull parameters α and u corresponding to different stress levels for the fatigue life data of PFRPCC as in Table 5, Eq. (7) has been used to calculate the design fatigue lives corresponding to selected acceptable probabilities of failure (P_f) i.e. 0.01, 0.05, 0.10, 0.15 and 0.25. The calculated design fatigue lives corresponding to selected probabilities of failure are listed in Table 6. The 'Design Fatigue Life Curves' have been generated, using the design fatigue lives for PFRPCC listed in above table and are provided in Fig. 3, 4 and 5 for PFRPCC containing 0.5%, 1.0% and 2.0% fibres respectively.

Table 6 – Design fatigue lives for PCC and PFRPCC

PCC -Design Fatigue Lives N_D					
Stress	P_f = 0.01	P_f = 0.05	P_f = 0.10	P_f = 0.15	P_f = 0.25
0.80	1416	2646	3487	4118	5126
0.75	16656	34494	47574	57734	74508
0.70	17143	45765	70609	91675	129317
0.65	21198	68078	113969	155426	233912
PFRPCC- 0.5% -Design Fatigue Lives N_D					
Stress	P_f = 0.01	P_f = 0.05	P_f = 0.10	P_f = 0.15	P_f = 0.25
0.85	2354	4573	6131	7315	9231
0.80	7192	14818	20390	24711	31833
0.75	17275	43053	64439	82148	113119
0.7	37352	105139	166055	218656	314216
PFRPCC- 1.0% -Design Fatigue Lives N_D					
Stress	P_f = 0.01	P_f = 0.05	P_f = 0.10	P_f = 0.15	P_f = 0.25
0.85	2043	4284	5941	7234	9376
0.80	8069	19577	28956	36651	49998
0.75	19416	55560	88392	116904	168968
0.7	37692	113216	184014	246524	362415
PFRPCC- 2.0% -Design Fatigue Lives N_D					
Stress	P_f = 0.01	P_f = 0.05	P_f = 0.10	P_f = 0.15	P_f = 0.25
0.85	1800	4013	5717	7075	9368
0.80	7920	21142	32619	42351	59741
0.75	12737	43764	75481	104802	161500
0.7	19715	72704	129375	183043	289148

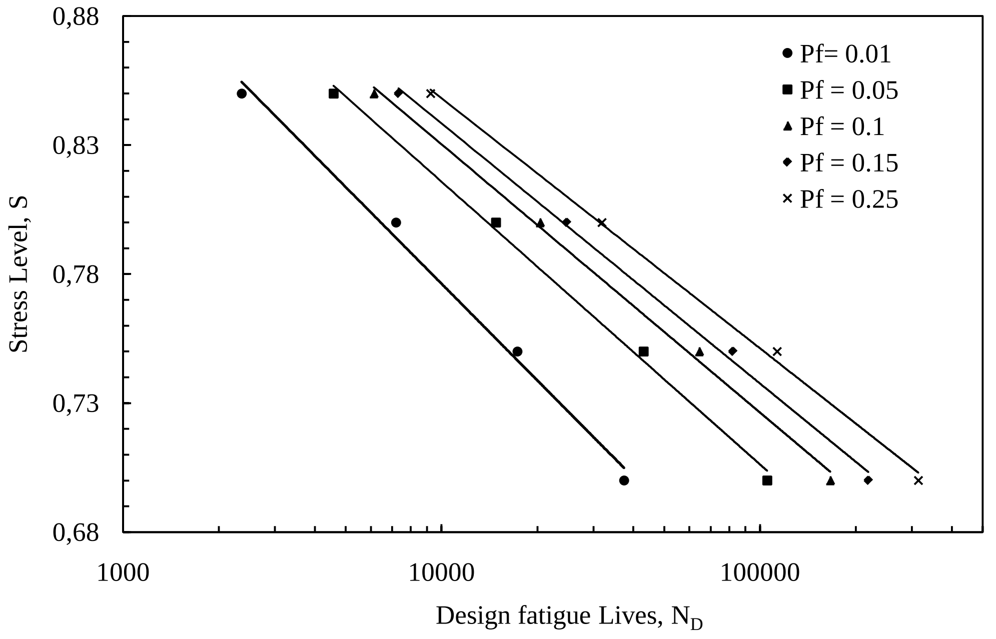

Fig. 3 Design fatigue life curves for PFRPCC-0.5%

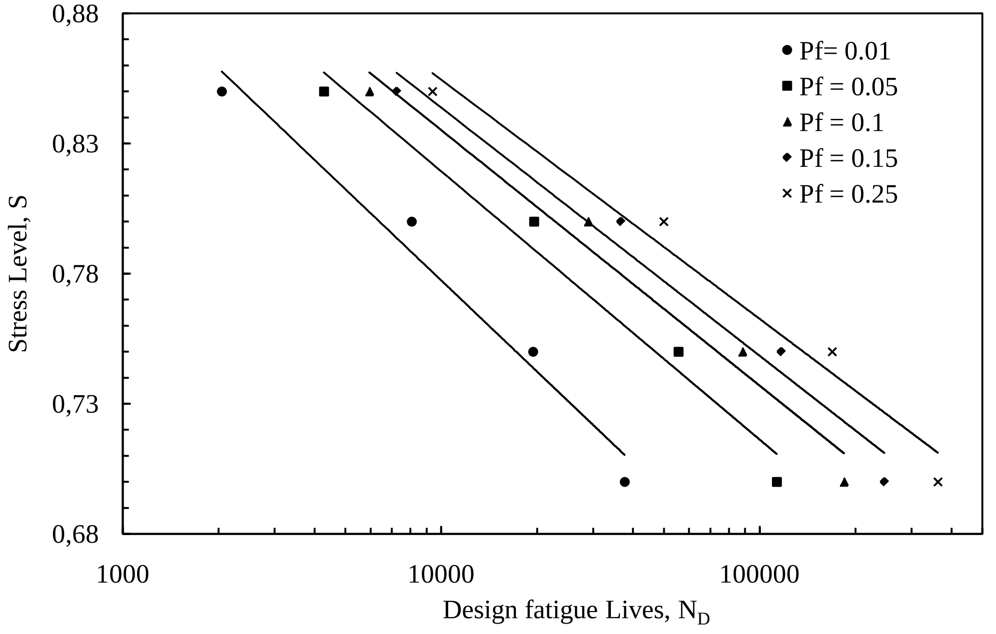

Fig. 4 Design fatigue life curves for PFRPCC-1.0%

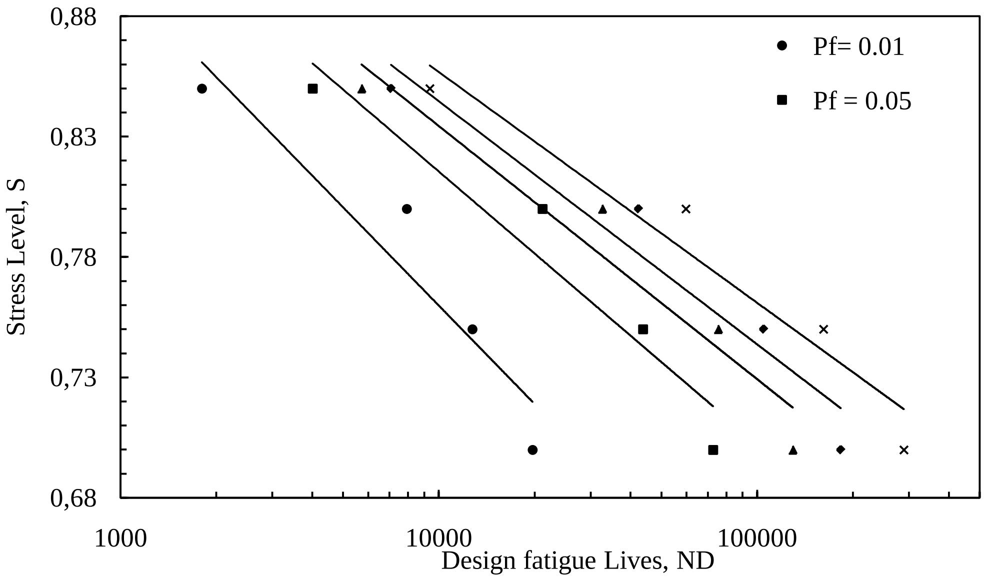

Fig. 5 Design fatigue life curves for PFRPCC-2.0%

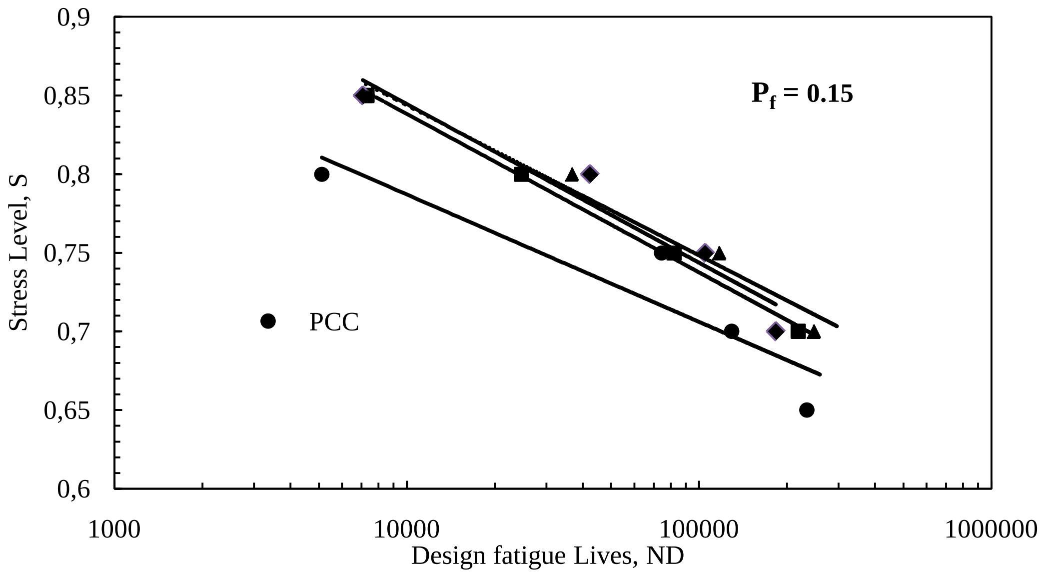

Fig. 6 Comparison of design fatigue life for PCC and PFRPCC

The fatigue life curves can be of great use to design engineers while designing for fatigue. Fig. 6 presents the comparison of design fatigue life curves for PCC with PFRPCC containing different amount of fibres. It can be observed that addition of fibres enhances the design fatigue life of the resulting material. The enhancement in design fatigue life is more pronounced up to addition of 0.5% fibres and thereafter with more addition of fibres, the increase in fatigue life is insignificant. This may be attributed to insignificant increase in static flexural strength beyond 0.5% fibre content.

It has been pointed out that the hazard function or risk function of the lognormal distribution, which was extensively used earlier for the statistical description of fatigue data, decreases with increasing life (n) or time, which is in violation of the physical phenomenon of progressive deterioration of engineering materials resulting from fatigue process [33].Thus the physical assumption of hazard function that increases with time leads to the Weibull distribution. It was indicated that the hazard function of the Weibull distribution increases with time or with an increase in the number of cycles for α>1.0 and different shapes of the hazard function can be obtained for different values of the shape parameter α[31].

The hazard function of the Weibull distribution is given by the following equation:

$$H_z(n) = \frac{\alpha}{u - n_{o,S}} \left(\frac{n - n_{o,S}}{u - n_{o,S}} \right)^{\alpha - 1} \tag{8}$$

Assuming the minimum life $n_{o,S}$ to be zero, the hazard function of Weibull distribution obtained through (8) employing the average values of shape parameter $\alpha$and characteristic life u, is plotted against number of cycles n some selected cases in Fig. 7. It can be observed from Fig. 7 that the hazard function increases with increase in number of cycles to failure for all the cases. It can also be seen that the addition of fibres to PCC leads to reduced risk of failure for the same number of cycles as compared to PCC.

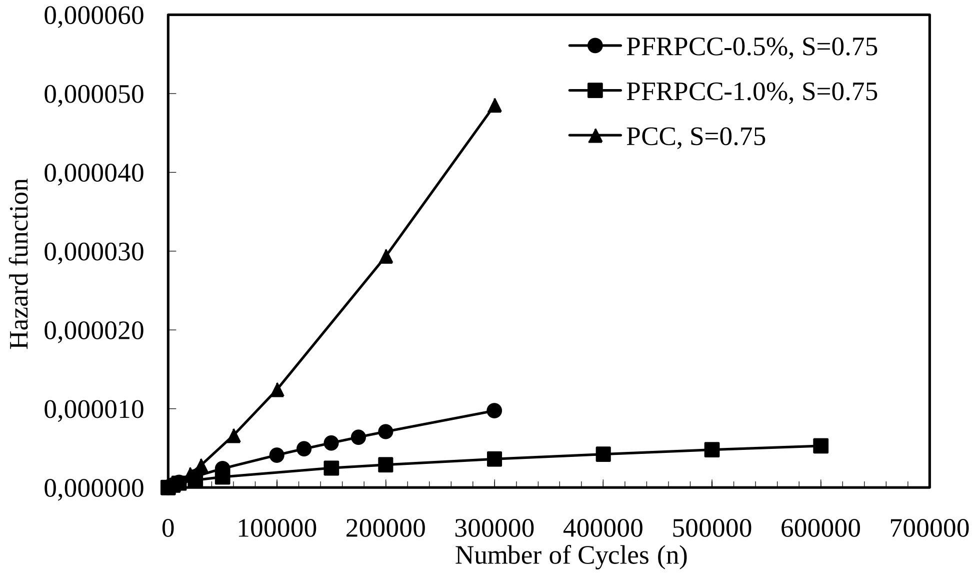

Fig. 7 Hazard function of Weibull distribution for selected cases

4 Conclusions

Fatigue life data for polymer concrete composites containing macro mono-filament type poly-propylene fibres has been analysed statistically. It has been observed that the fatigue life distributions at various stress levels for PFRPCC approximately follow a two parameter Weibull distribution. Values of Weibull parameters have been obtained by various methods. It is observed that addition of fibres into PCC enhances the static strength as well as fatigue lives of the resulting material, but this is at the cost of increased variability in fatigue lives. This conclusion is drawn as the values of weibull shape parameter for PFRPCC at various stress levels is lower than those obtained for PCC. Further, fatigue life data has been used for obtain the design fatigue lives for various probabilities of failure and design fatigue life curves have also been generated.

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